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Application and Prospects of Artificial Intelligence (AI)-Based Technologies in Soil Science

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Abstract
Artificial intelligence (AI) can assist soil health studies in agriculture by collecting information, monitoring weather patterns, and recommending the use of pesticides and fertilizers. Farmers may increase productivity and profitability at the same time by using farm management software to make smarter decisions at every stage of the crop-cultivation process. AI is used in soil research to build comprehensive soil health maps and forecast changes by combining data from IoT sensors, GIS, and soil samples. By providing data-driven, localised recommendations, AI-driven models can improve digital soil map resolution, predict soil parameters more accurately, and assist precision agriculture decision-making processes. Promising paths for expanding AI in agriculture are provided by developments in 5G technology, edge computing, and sensor miniaturisation. Machine learning (ML) has completely changed soil science over the last 20 years, transforming soil system assessment, modelling, and management. By combining soil metrics, meteorological data, and other environmental elements for accurate and effective fertility estimate, recent developments in machine learning (ML) and artificial intelligence (AI) present intriguing options.

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INTRODUCTION

As the growing population is increasing rapidly day by day, so it is essential to increase the agricultural production by exploring the innovative or smart technology to sustain agriculture. Artificial intelligence integration into agriculture played a significant role in other new advancement technologies such as vast data analytics, the internet of things, drone technology, sensors & cameras and widespread connectivity across the remote areas/fields. The interpretation data on soil management includes weather, temperature, soil moisture and soil conditions, ancestral crop performance history, it also offer a best advance technology to predict the optimum time for planting and harvesting crop for specified regions. This technology will not only boost the crop yields but also help to minimize the environmental impact, lower food prices, enhance worker safety, also reduces the usage of water, fertilizers, pesticides and ensure that the food production could meet the demands of the growing population (Gupta and

Pal, 2025). Artificial Intelligence (AI) has emerged as a transformative force in modern agriculture, offering unprecedented opportunities to enhance soil organic matter (SOM) dynamics, nutrient cycling efficiency, and water productivity. Soil health-led intensification the strategy of boosting agricultural productivity while restoring and sustaining ecological functions requires timely, precise, and spatially explicit information on soil processes. Traditional soil monitoring methods are often labor-intensive, infrequent, and unable to capture the complexity of interactions among soil organic matter, nutrients, microbes, and water. The integration of AI with conservation agriculture, precision fertilization, and climate-smart management further supports the synergistic improvement of SOM stabilization and water-use efficiency. AI-driven soil health innovations represent a pivotal pathway toward sustainable intensification. By enabling precise management of SOM, nutrient cycling, and water resources, AI offers the potential to enhance productivity, resilience, and environmental sustainability across diverse agro-ecosystems. Soil-health-led intensification seeks to raise yields while rebuilding SOM and improving ecosystem services (Kumar *et.al*. 2025). Studies synthesizing the mechanisms by which SOM improves structure, water retention and nutrient buffering demonstrate that practices increasing organic inputs rotating with cover crops, integrating manures/composts and lowering tillage intensity strengthen soil structure and sequester carbon, but their outcomes vary by soil type and context (Hatano, 2024; Krupek *et al*., 2022). AI tools can accelerate the tailoring of these practices to local conditions by predicting where particular interventions will most effectively increase SOM, reduce nutrient loss and boost water productivity enabling precision intensification that is both productive and restorative.

APPLICATION OF AI IN SOIL SCIENCE

Soil organic carbon (SOC), a crucial measure of soil health, promotes the process of carbon storage. Strong plant development is supported by enhanced soil fertility, structure, and moisture retention, all of which are linked to high SOC levels (Lehmann *et al*., 2020). Enhancing SOC levels through techniques like cover crops, no-till farming, and adding organic matter to the soil can boost agricultural output while lowering greenhouse gas emissions. However, stored carbon is released back into the atmosphere when soil erosion or degradation occurs, which contributes to global warming. AI in agriculture systems can identify factors affectingcrop yields, such as temperature and moisture levels, allowing farmers toadjust sowing, irrigation, and fertilization practices accordingly. Research indicates that precision agriculture can increasecrop yields by 20-30% by minimizing waste and maximizing productivity. Soil testing can involve a variety of techniques and fertilizer recommendations to determine the soil's fertility and pinpoint any deficiencies that need to be addressed. Soil analysis provides information useful to farmers and consumers in deciding when and how much fertilizer and farmyard manure should be administered during a crop's growth cycle (Zayani *et al*., 2023). Soil erosion, water pollution, low microbial activity, and increased production costs are all consequences of agriculture's overuse of fertilisers and pesticides. This is important for sustainable agriculture because it affects crop growth, nutrient balance, and environmental preservation. However, laboratory testing is a part of standard soil testing procedures, making them expensive, time-consuming, and not easily accessible to farmers. Decision-making delays brought on by such problems can result in long-term soil degradation and ineffective fertiliser use. An AI-based Soil Fertility Prediction System was created to deal with these problems.

APPLICATION OF AI IN SOIL HEALTH AND QUALITY ASSESSMENT

Enhancing soil health and quality assessment is possible through the integration of artificial intelligence and soil science. Despite the enormous obstacles, the undertaking is valuable due to the potential advantages of better soil management techniques and higher agricultural production. The objectification of AI into soil wisdom is a pivotal advancement in assessing and covering soil health and quality. Artificial intelligence (AI) can quickly and accurately interpret vast volumes of data to support decision-making processes that increase productivity and reduce resource consumption (Abdulraheem *et.al.*, 2023). These advancements have led to a greater use of AI in agriculture, including precise irrigation, automated harvesting, disease diagnosis, and crop monitoring.

The significance of soil health is growing with agricultural evolution, especially in relation to environmental sustainability and global food security. Because standard soil testing procedures are expensive, time-consuming, and labor-intensive, they have limits when it comes to assessing soil health. Results from the collection, transportation, and ensuing chemical analysis can be obtained in a matter of days or weeks and necessitate substantial field work. Important choices for improving soil management techniques may be postponed by this drawn-out procedure.

This is being altered by AI, which makes soil assessment quicker, more precise, and more thorough. AI can analyze enormous volumes of data in real time to assess soil health by combining machine learning (ML), sensor technologies, and data analytics.

IMPROVING SOIL ASSESSMENT WITH REMOTE SENSING AND AI

In order to give a more comprehensive picture of soil conditions, AI uses remote sensing technologies in addition to ground sensors. Data on soil composition, moisture distribution, and erosion patterns are gathered in vast quantities by satellites, drones, and spectral imaging equipment. Following data processing, AI creates high-resolution soil maps, providing farmers with a thorough understanding of their property and assisting them in making better decisions.

Manual testing is no longer necessary because machine learning models based on spectral reflectance data can identify different types of soil and nutrient deficiencies. Additionally, AI-powered remote sensing aids in the early detection of soil deterioration indicators, enabling farmers to take action before problems worsen. In particular, the combination of AI and remote sensing makes soil monitoring more cost-effective and efficient for major agricultural operations.

USING AI TO PREDICT SOIL MANAGEMENT

AI is essential not just for real-time monitoring but also for forecasting future soil conditions. Artificial intelligence is able to predict changes in soil health and suggest methods for preserving long-term fertility by examining past soil data, cropping patterns, and climatic trends. AI can enhance soil sustainability by using deep learning and reinforcement learning techniques to optimize crop rotation, irrigation, and fertilisation schedules. Precision agriculture powered by AI guarantees that resources are used only where they are required, cutting waste and lessening its negative effects on the environment. By encouraging more sustainable agricultural methods, this data-driven strategy not only increases soil health and productivity but also contributes to long-term food security.

CHALLENGES FACED BY AI IN AGRICULTURE

Implementing AI in agriculture is more than just a technology upgrade; it's a shift in how we manage our food systems. While the potential for precision and efficiency is massive, the hurdles are equally significant. Here is a breakdown of the core challenges currently facing AI in agriculture.

1. Technical and data constraints

AI depends on the quality of the data it uses. In agriculture, gathering that data is notoriously difficult.

- Environmental Noise:Unlike a controlled factory, a farm is unpredictable. Dust, varying light conditions, and extreme weather can interfere with sensors and cameras, leading to "noisy" data or hardware failure.
- Data Fragmentation: Agricultural data is often stored in soils. Different companies use different formats, making it hard for an AI to integrate

soil data from one sensor with weather data from another.

- The "Black Box" Problem: Many complex AI models (like deep learning) provide a result without explaining why. A farmer might be hesitant to destroy a crop just because an algorithm said it "might" be diseased without seeing the reasoning.

2. Infrastructure and Economic Barriers

The cost of entry is just too expensive for many people.

- Connectivity Issues: AI often requires cloud processing. Many rural areas, particularly in developing nations, lack the high-speed 5G or stable internet needed to transmit large volumes of data from field sensors to the cloud.
- High Upfront Investment: The cost of drones, autonomous tractors, and IoT sensor networks is significant. For smallholder farmers, the Return on Investment (ROI) can take years to realize, making it a risky financial gamble.
- Electronic Waste: As hardware becomes obsolete or breaks under harsh field conditions, it contributes to "technotrash." Discarding lead, mercury, and lithium batteries from agricultural robots poses a new environmental risk.

3. The Human and Social Gap

Technology often moves faster than the people using it can adapt.

- Skill Deficiency: Using AI requires a blend of agronomy and data science. There is currently a massive gap in training; many farmers are experts in biology but may struggle with the technical troubleshooting of a malfunctioning algorithm.
- Loss of Intergenerational Knowledge: There is a fear that over-reliance on AI might erode the traditional "gut feeling" and observational skills passed down through generations of farmers.
- Labor Displacement: While AI can solve labor shortages in some regions, in others, the automation of tasks like harvesting or sorting threatens the livelihoods of seasonal migrant workers.

4. Ethical and Legal Hurdles

Who owns the data, and who is responsible when things go wrong?

- Data Sovereignty: When a tractor collects data on a farmer's soil, who owns that data? Large tech corporations often aggregate this information, which could potentially be used to manipulate market prices or land values.
- Algorithmic Bias: If an AI is trained primarily on data from large industrial farms in the West, its recommendations might be completely ineffective or even harmful when applied to small-scale tropical farms with different soil chemistry.
- Liability: If an AI-driven drone misidentifies a pest and applies a toxic amount of pesticide that ruins a neighbor's organic crop, the legal framework for who is at fault (the farmer, the software developer, or the hardware manufacturer) is still largely undefined.

Table 1: **Barriers to AI adoption**

Category	Primary challenge	Impact on farming
Financial	High capital expenditure	Limits technology to wealthy or corporate farms.
Environmental	Hardware durability	Sensors fail in heat, mud, and rain.
Ethical	Data privacy	Farmers fear corporate exploitation of their data.
Technical	Internet latency	Real-time AI processing is impossible in dead zones.

OBSTACLES IN AI-POWERED SOIL MONITORING

Even though AI has the potential to revolutionise soil quality monitoring, a number of obstacles must be overcome before it can be widely used. The quality and accessibility of data are among the main obstacles. Large datasets are necessary for training AI models, but in many areas, the data is either inconsistent or insufficient. Furthermore, it is challenging to create AI algorithms that can produce precise and trustworthy findings in a variety of contexts due to the absence of standardised data collection techniques.

Cost is still another important consideration. Smallholder farmers are disadvantaged by the high cost of sophisticated AI-driven sensors and monitoring tools, which are more affordable for large commercial farms. Financial obstacles continue to prevent mainstream use of AI, despite efforts to create more reasonably priced solutions.

Additionally, AI models need to be updated frequently to take into consideration shifting agricultural methods, soil composition, and climatic changes. This necessitates continuous research, technical know-how, and infrastructure support-all of which aren't always easily accessible, especially in developing nations. (wu *et.al.*, 2008). Furthermore, a certain degree of digital literacy is necessary for the effective application of AI in agriculture, which might be difficult to achieve in rural areas with little access to training and technology. Resolving these issues will be essential to guaranteeing that AI-powered soil monitoring is practical and affordable, enabling farmers of all sizes to take advantage of its potential.

CONCLUSION

AI has the opportunity to revolutionise soil science by improving land management's sustainability, accuracy, and efficiency. Improved fertilisation techniques and land development can result from AI's ability to detect nutrient deficiencies, forecast soil erosion, and evaluate the general health of the soil. AI has the potential to boost crop yields and lessen environmental impact by improving the timing and distribution of agricultural resources. More sustainable land management techniques can result from the identification and remediation of soil deterioration with the aid of AI-powered solutions. AI has the potential to help conserve water and lessen dependency on artificial fertilisers by optimising the use of nutrients and water. The difficulties presented by various agricultural environments and intricate soil systems must be addressed by ongoing study and development of AI-powered models. It needs cooperation between academics, professionals, and industry participants to turn AI developments into workable solutions. AI has the potential to transform soil research and support productive and sustainable agriculture, to sum up.

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